J MATER RES TECHNOL. 2019;8(5):4094–4107

Available online at www.sciencedirect.com

jmr&t
Journal of Materials Research and Technology
www.jmrt.com.br

Original Article

Fire resistance performance of concrete-PVC panels with polyvinyl chloride (PVC) stay in place (SIP) formwork

Michel Murillo A.[a,b,*], Bernardo F. Tutikian[c], Vinicius Ortolan[c], Marcos L.S. Oliveira[d], Carlos H. Sampaio[e], Leandro Gómez P[a], Luis F. Silva O[a]

[a] Universidad de la Costa, Barranquilla, Colombia
[b] PPGE3M - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil
[c] Universidade do Vale do Rio dos Sinos, São Leopoldo, Brazil
[d] Faculdade Meridional IMED, Rio Grande do Sul, Brazil
[e] Departament d'Enginyeria Minera, Industrial i TIC, Serra Húnter Prof., Universitat Politècnica de Catalunya Barcelona Tech, Av. Bases de Manresa 61–63, Manresa, 08242 Barcelona, Spain

ARTICLE INFO

Article history:
Received 2 January 2019
Accepted 11 July 2019
Available online 26 July 2019

Keywords:
Concrete panels
Fire resistance
Precast concrete
PVC encased system
Stay-in-place formwork

ABSTRACT

Stay-in-place (SIP) formwork is a more-practical alternative to traditional steel or wood formworks due to its improved constructability and durability. The aim of this paper was to study the fire resistance performances of structural and non-structural concrete panels with polyvinyl chloride (PVC) SIP formwork. Three 124.01 in × 110.24 in × 3.15 in panels of PVC SIP formwork were tested and compared to one another. All panels were aged for 28 days, then exposed to the standard fire curve based on the ISO 834:2014 standard, and the temperatures in each panel surface recorded. The results indicate that concrete strength significantly influenced the structural stability and the fire resistance time of the panels (under load), even in this type of panels when exposed to high temperatures. It was found that the PVC encasement enhanced the thermal insulation property, one of the fire resistance performance criteria. Overall, the importance of this alternative formwork is the reduction in the use of forest resources, the raise of awareness of their conservation, and the promotion of their rational use as this a material is friendly to the environment.

1. Introduction

From the earliest times, fire has been considered as one of the elemental forces on Earth [1]. It possesses both powerful destructive and constructive properties, depending on its usability. Fire's captivating flame can fascinate, its heat and light can help in sustaining lives, and its elemental energy ushers the technological civilization; however, in an uncontrolled stage, fire can cause severe destruction and even loss of life [1,2]. Although data demonstrate that, in general, fire death rates per million population have been decreasing over

* *Corresponding author.*
E-mails: mmurillo4@cuc.edu.co (M.M. A.), bftutikian@unisinos.br (B.F. Tutikian), vkortolan@gmail.com (V. Ortolan), msilva@cuc.edu.co (M.L. Oliveira), carlos.hoffmann@upc.edu (C.H. Sampaio), lgomez52@cuc.edu.co (L. Gómez P), lsilva8@cuc.edu.co (L.F. Silva O).
https://doi.org/10.1016/j.jmrt.2019.07.018

the past decades [3], in countries like the United States, Denmark, Japan, and the Czech Republic, an increase in the fire death rate per million population has been recorded [4]. In 2013, more than three million fires [5] resulted in a death toll of over 21,000 and a rate of wounded people of more than 65,000 [6]. Fire always begins with an ignition of a material, and continues until the flame spreads to all combustible surfaces. This stage is the start of the fully developed stage of the fire, which is critical for structural elements due to the fact that they start to lose their strengths and load-bearing capacities [2–7]. During the fire event, the flames interact dynamically with their surroundings and their temperature and intensity depend on different factors such as the mass and the nature of available combustibles, the degree of ventilation, and the internal area of the combustion chamber. Most materials degrade due to their exposure to any of these fire conditions [2].

Concrete is the most widely used construction material worldwide [8] (roughly 25 billion tons are manufactured each year [9]), offering versatility for structural and architectural considerations to the designer. Formwork is basically, a temporary structure whose function is to support and confine the fresh concrete until it has cured long enough to keep upright by itself. In addition to ensuring safety, formworks can account for a significant cost within the overall price of a concrete structure, especially for those formworks fabricated on site [8]. Thus, if proper attention is given to formwork design and construction, significant reduction in cost and accidents will result.

Due to increasing tighter construction schedules, formwork stripping is necessary to keep a project on schedule; however, it often leads to stripping of formwork before concretes from gaining sufficient strengths [10]. Recent advancements in materials technology have introduced various polymers into civil applications [11–13].

On the other hand, Polyvinyl Chloride (PVC) is a polymer-based material, extensively used in construction industry [14] as a low-maintenance material, mainly in Ireland, the UK, and the USA [15]. PVC is one of the most important commercial plastics for its low costs and excellent properties: high electrical insulation, high resistance to abrasion, low diffusion for humidity, remarkable resistance to water, bases, acids, alcohols, oils, low creep deformation, durability and mechanical stability [15–17]. The thermal conductivity of PVC is only 0.45%–0.6% of a steel tube, thus it provides a stable curing condition in the high performance and durability of the core concrete [18,19].

Currently stay-in-place (SIP) formwork is being employed worldwide in concrete construction as a viable alternative to conventional formworks (wood or steel), due to its multiple advantages in mechanical, environmental, and economic aspects [20,21]. PVC is commonly used as a SIP formwork for its lower cost compared to other materials such as fiber-reinforced polymers, its durability, and easy assembling procedure, developed as a solution for fast, secure, and convenient concrete construction. This type of formwork has been mainly employed in commercial, agricultural and industrial buildings [22,23]. The PVC SIP formwork consists of interconnected panels, which not only serve as permanent formwork for the concrete walls but also encase the wall surface. This system is commonly used to build foundations, retaining walls, walls in water and waste treatment tanks, as well as walls for swimming pools [23].

PVC SIP formwork offers some important advantages to the concrete mechanical properties, like the increase of structural strength, the improvement in durability, and the protection to corrosion [2]. However, such advantageous characteristics have not been fully addressed by the existing codes, such as CSA [24] and ACI [25]. Thus, Chahrour et al. [26] revealed that the cracking load, the yield load, and ultimate load were increased by 36%, 78% and 36% on average, respectively, compared to the conventional system. In addition, the ductility index for this same system specimens increased by 25%. Regarding environmental issues, the PVC SIP formwork is highly applied to infrastructure construction in marine and saline aggressive environments, where polymer shells act as barriers to prevent the entry of carbon dioxide and chlorides into embedded concretes [21]. In comparison to conventional formwork, PVC SIP one is left in place permanently with the constructive element (column, wall, pool, etc.), becoming part of the finished structure and conferring a protective cover to concrete. Moreover, PVC helps in the prevention of any moisture loss, necessary for the setting and hydration of fresh concrete as well as in the elimination of time-consuming and costly-curing processes. It also helps in the protection of concretes against thermal changes, and in the improvement of impermeability by confining the concrete cores [23].

In the context of standardization, EN 1991-1-2: 2002 [27] relates the actions in the structure when exposed to fire, which includes the main concepts and rules necessary to describe thermal and mechanical actions in structures, however nothing contained when the structuring element is coated with PVC SIP formwork. Nevertheless, when the behavior parameters of the components are not known, it becomes necessary to analyze with a procedure based on a nominal (standard) fire, in this way the classification system takes into account the individual characteristics. In addition, the code EN 1996-1-2: 2005 [28] presents guidelines for masonry design, there is nothing related when the system is a formwork stay-in-place type, reinforcing the need for characterization and performance period against the action of a standard fire, according to the test procedure of EN 1363-1:1 1999 [29].

Despite the above-mentioned findings and advantages in the improvements of concrete mechanical properties with this new system of encasement, very few studies in the literature have reported on its fire resistance behavior. Hence, the main objective of this study was to analyze and compare the fire resistance performance of different PVC stay-in-place formwork concrete panels with, and without, load. This investigation will certainly broaden the knowledge on this subject for the scientific society in the area of civil construction and materials science.

2. Experimental procedures

The fire resistance of three (3) PVC SIP formwork encased concrete panels was evaluated in accordance with ISO 834 [30]. The main objective of this test carried out for all of them was to determine the safety and the fire resistance time of the con-

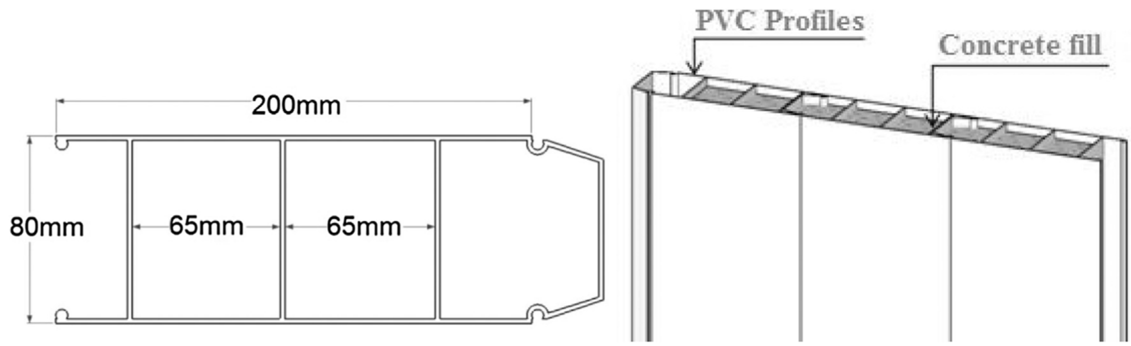


Fig. 1 – Illustration of the (a) PVC profiles geometry and the (b) panels composition.

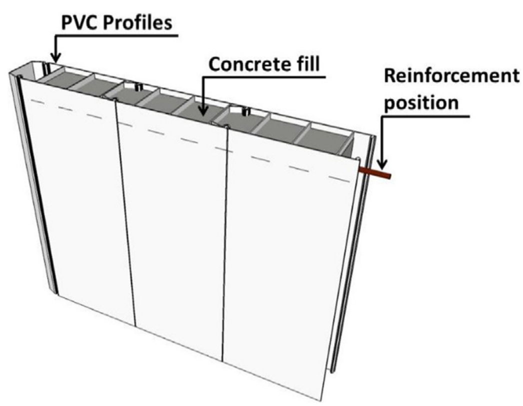


Fig. 2 – Illustration of the cross-section of the panels and the reinforcement position.

Table 1 – Mix design of the concretes used.

Mixture components	Quantity
Cement	360 kg/m3
Coarse aggregate	909 kg/m3
Fine aggregate	340 kg/m3
Water	198 lt
Additive	3,5 kg/m3

crete panels, based on three parameters: thermal insulation, integrity and structural stability.

2.1. Panels

In this experiment, two SIP formwork panels with load-bearing capacity and one without it, were tested and compared with each other. The SIP formwork systems with load-bearing capacity consisted of white modular polyvinyl chloride (PVC) profiles coupled to each other through fittings and filled with self-compacting concrete with different mix designs. The coarse aggregate maximum dimension was 0.374 in.(9.5 mm). PVC profiles had a total thickness of 3.15 in.(80 mm), a width of 7.87 in.(200 mm), and a wall thickness of 0.67 in.(1.7 mm) with two internal ribs every 2.55 in.(65 mm), thus forming a dimension sample of 124.01 in × 110.24 in × 3.15 in.(3150 mm × 2800 mm × 80 mm). The density and the Charpy impact strength of the PVC were approximately 1450 kg/m^3 and 18.5 kJ/m^2, respectively. The fire reaction of the samples is about the flame spread index is 7.56 and the maximum specific smoke density (Dmc) is 281.13.

The self-compacting concrete of the first sample (PVC1) had a SF2 of 25.6–29.5 in.(650–750 mm) spreading class, an apparent plastic viscosity class of t500 s/2, a compressive strength of 1.45 ksi (11 MPa) and a bulk density of 2300 kg/m^3. Whereas, the self-compacting concrete of the second sample (PVC2) had a SF2 of 25.6–29.5 in.(650–750 mm) spreading class, an apparent plastic viscosity class of t500 s/2, a compressive strength of 2.9 ksi (20 MPa), and a bulk density of 2300 kg/m^3.

The third and last sample (PVC3), without load-bearing capacity, had a total area of 124.01 in × 118.1 in × 2.94 in.(3150 mm × 3000 mm × 74.7 mm) and shared the same properties of PVC2 materials, except for the Charpy impact strength of PVC of 14 kJ/m^2. The self-compacting concretes used in the filling of all PVC molds were modified with a plasticizer additive to ensure fluidity and all the panels carried out only reinforcement on the lashing strap at the top of all walls. Likewise, all these concretes kept the mix designed that the Table 1 shows.

The use of self-compacting concrete in this research is due to the ease of compacting the concrete in small spaces such as the one enclosed by this kind of panels systems. Thus, with this type of concrete it was possible to avoid the application of vibrators for its compaction. In a similar way, concretes with low grades of compressive strength were chosen taking into account that being inside the system and being protected by permanent PVC formworks, it does not need high resistances neither for load factors nor for durability.

All samples were aged for 28 days and, then fixed on a metal frame structure with screws, and sealed with an elastomeric fire-resistant sealant for the tests. Table 2 summarizes the main characteristics of the materials of all tested samples and Figs. 1 and 2 show their geometry.

2.2. Methods

All tests were performed in a standardized and calibrated vertical furnace at the Technological Institute in Civil Construction Performance of the Unisinos University (itt Performance). The furnace was heated with four liquefied petroleum gas burners and controlled by differential pressure. Two burners were installed at the sidewalls of the furnace and then calibrated to increase the temperature according to the standard temperature-time curve established by ISO 834 [30] and EN 1991-1-2:2002 Standards, given by the equation 1

Table 2 – Main features of specimens used in tests.

Material	Parameter	PVC1	PVC2	PVC3
PVC profile	Dimensions, in. (mm)	91.22 × 3.15 (231.7 × 80)		
	Wall thickness, in. (mm)	0.67 (1.7)		
	Spacing of reinforcement, in. (mm)	2.75 (70)		2.91 (74)
Concrete	concrete compressive strength, ksi (MPa)	1.45 (11)	2.90 (20)	
	Reinforcement details	Only on the spars and backstops		
	Formwork type	SIP		

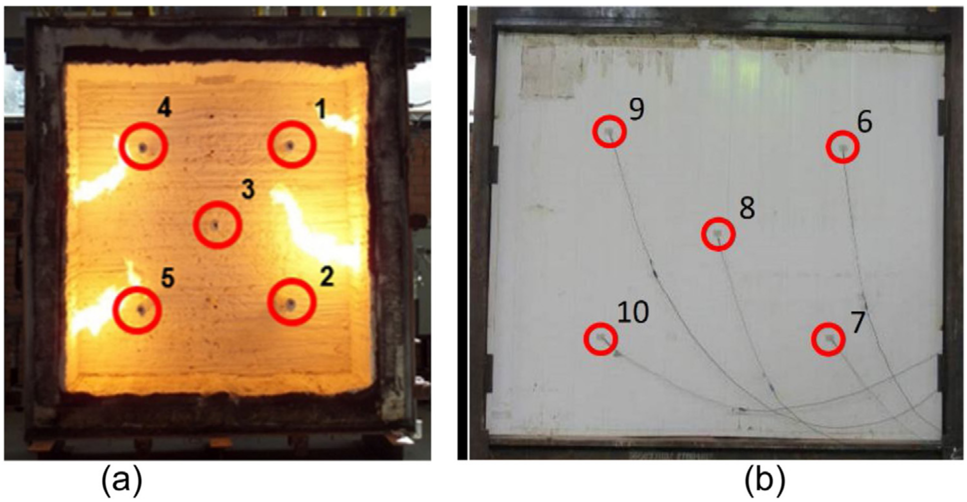


Fig. 3 – Numbering of (a) thermocouples inside the furnace and (b) outside.

Table 3 – Equipment used in the experiment.

Equipment	Model	Technical description
Thermographic camera	FLIR / A325	Minimum capacity: 0 °C (32 °F) Maximum capacity: 350 °C (662 °F) Resolution: 1 °C (33.8 °F)
Chronometer	Extech Instrument 365535	Minimum capacity: 0:00':00"1 s Maximum capacity: 9:00':99"9 s Resolution: 1/100s
Vertical furnace	Grefortec GFT 03276 FG	Capacity: 1200 °C (2192 °F) Resolution: 0.01 °C (32.02 °F)
Laser tape	Bosch - GLM 150 Professional	Minimum capacity: 0 in. (0 mm) Maximum capacity: 5905.51 in. (150,000 mm) Resolution: 0.04 in. (1 mm)
Thermo-hygrometer	Instrutemp ITMP 600	Minimum capacity: 10 °C/20%/20 dB(A)/0Lux Maximum capacity: 60 °C/80%/130 dB(A)/2000Lux Resolution: 0.1 °C/0.1%RH/0.1 dB(A)/1Lux

[27]. The total heating power of the furnace was 65,400 kcal/h, procedure previously adopted in other studies [6,31,32].

$$\theta g = 20 + 345\,\mathrm{Log}10(8\,t + 1), \quad (1)$$

Where θg is the gas temperature in the fire compartment (°C) and t is the time (min).

The samples were coupled to the furnace and continuously monitored by 5 thermocouples with a 0.59-inch (1.5 mm) diameter on the surface exposed to fire and other 5 thermocouples with a 0.27-inch (0.7 mm) diameter on its surface not exposed to fire. The position and numbering of internal thermocouples (face exposed to high temperatures) are depicted in Fig. 3(a) and those of external thermocouples (face not exposed to high temperatures) in Fig. 3(b). The positions of the thermocouples 6–10 (external) coincide with the positions of the thermocouples 1–5 (internal) and responded the precept of the norm [33]. The temperatures were recorded every 30 s during the tests and with an accuracy of ±1.5%.

Moreover, a thermographic camera, a chronometer, and a laser tape were used to perform the control tasks. Table 3 presents a brief description of the equipment used in this study.

The test procedure used in this experiment was prescribed by ISO 834 [30]. The test determined the fire resistance times of the samples when exposed to the heating program described by the norm. The load-bearing capacity, integrity, and thermal insulation of the system were checked during the test. The load-bearing capacity is defined as the ability of a load-bearing element to support its test load without exceeding the specified criteria of deformation [30]. Integrity refers to the ability of a separating element when exposed to the fire on one side, to prevent the occurrence or passage of flames and hot gases

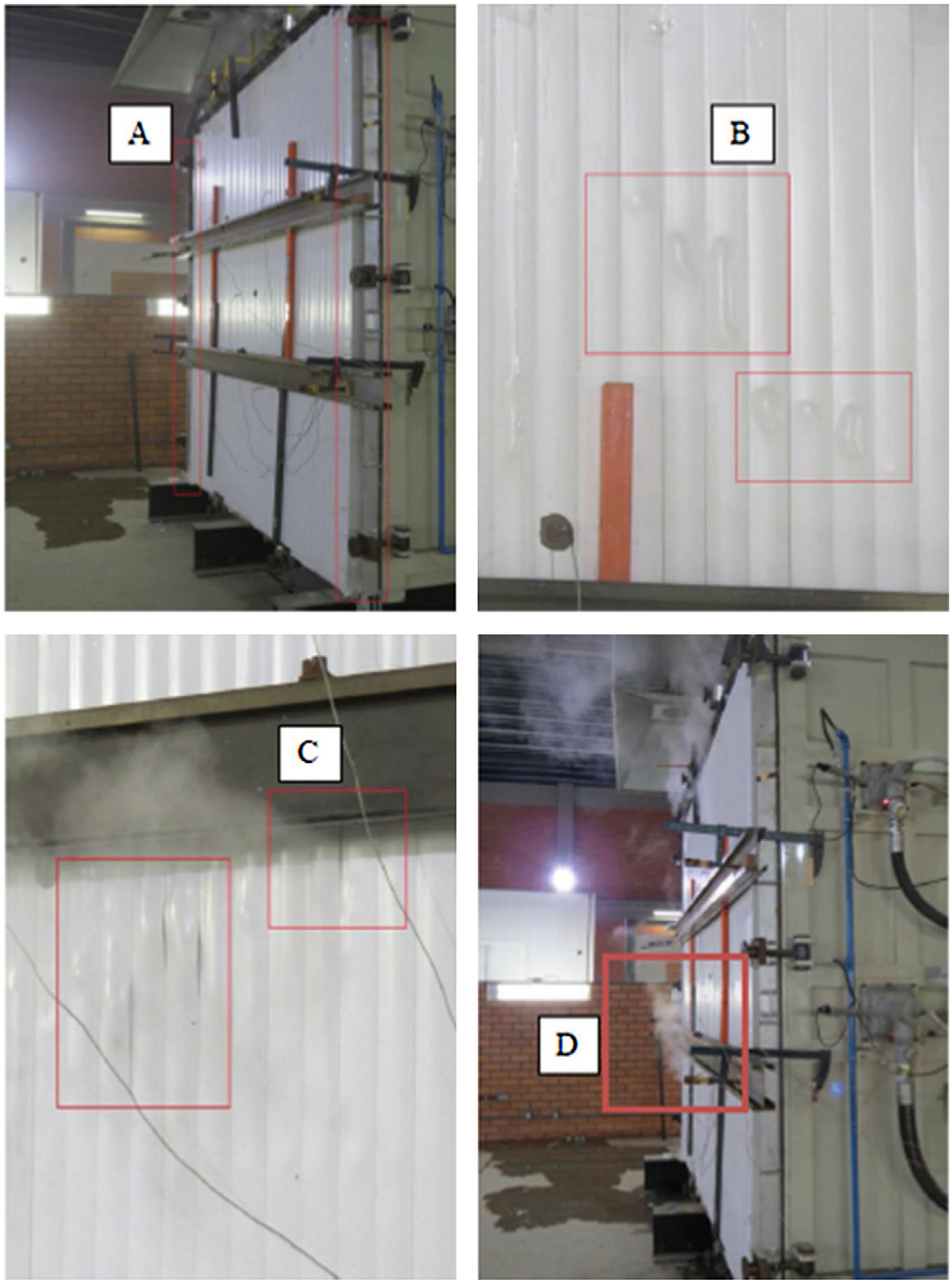


Fig. 4 – Main events occurring in the PVC3 sample test: slight buckling (A), deformation of the PVC profile (B and C) and leakage of gases through the panel (D).

on the unexposed side to the fire in a building construction. Thermal insulation is the ability of a separating element when exposed to the fire on one side, to restrict the temperature rise of the unexposed face to the fire in a building construction to below specified levels [30].

Thus, the temperature was measured with thermocouples. In addition, a thermographic camera and a laser tape were used to monitor and measure the horizontal deformation. Likewise, all results were visually inspected during the whole procedure.

3. Results and discussion

The testing of PVC1 lasted 26 min (min.). After the first 4 min of the experiment, a release of white smoke followed by crackles was observed. Between minutes 18 and 23, bubbles formed on the PVC surface not exposed to fire and some smoke was observed between the profiles near the center of the sample. Finally, at minute 26, an explosive crevice was developed in the concrete, which resulted in the loss of integrity of the system.

Fig. 5 – Appearance of bubbles on the PVC surface not exposed to fire of each sample.

Table 4 – Summary of the main events recorded during the tests performed.

PVC1	PVC2	PVC3
0 min: Pre-loading start	**0 min: Pre-loading start**	–
10 min: Pre-loading end	**15 min: Pre-loading end**	–
0 min: Start of the thermal program (loading and heating)	**0 min:** Start of the thermal program (loading and heating)	**0 min:** Start of the thermal program (heating)
1 min: Smoke release	**1 min:** Smoke release	**8 min:** Panel buckling
4 min: Cracking noises	**9 min:** Start of the melting of PVC	**11 min:** Cracking noises
8 min: Flow of a black liquid	**11 min:** Cracking noises inside the oven	**17 min:** Bubbles formation in PVC
18 min: Bubbles formation in PVC	**13 min:** Cracking noises inside the oven	**30 min:** Passage of smoke outside on the top
23 min: Smoke release in the central area	**18 min:** Bubbles formation in PVC	**31 min:** Passage of smoke outside on the bottom
26 min: Failure by loss of integrity	**27 min:** Smoke release in the central area	**32 min:** Smoke increase on top
26 min: End of the test	**29 min:** Cotton wool pad test	**60 min: End of the test**
–	**30 min:** Cracking noises inside the oven	–
–	**58 min:** Cotton wool pad test	–
–	**68 min:** Cotton wool pad test	–
–	**70 min:** Cotton wool pad test	–
–	**72 min:** Cotton wool pad test	–
–	**75 min:** Cotton wool pad test	–
–	**80 min: End of the test**	–

The testing of PVC2 lasted 80 min. After the first 9 min of exposure to fire, PVC2 started to melt. Between minutes 11 and 13 crackles were heard inside the oven. Between minutes 18 and 27 bubbles formed on the external face of the sample and smoke was released at the center of the sample.

The testing of PVC3 lasted 60 min. After minute eight, a slight local buckling was noticed in the sample. At minute 17, a slight fusion reaction occurred at the PVC profile of the external surface of the sample, which deformed the profile although it had not reached a full liquid state at that moment. At exactly minute 30, gases began to leak through the wall.

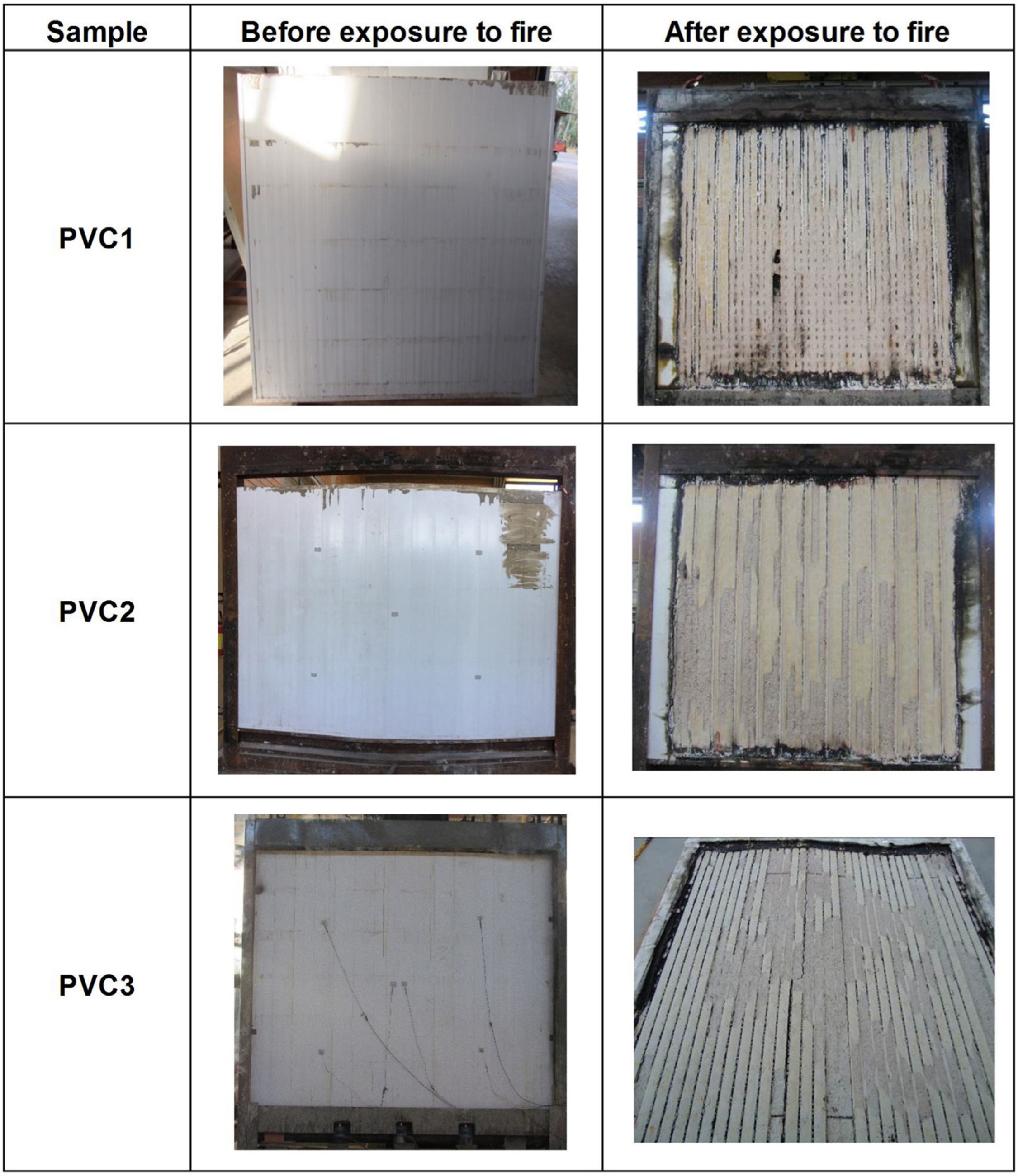


Fig. 6 – Initial appearance vs spalling of concrete on the face exposed to fire of each sample.

Fig. 4 gives evidence of how this event developed during the entire test.

Comparing the outcome of this test with other studies not involving the use of PVC [6,31,32], it can be observed that this material helps to delay the reaction time, which may facilitate human evacuation from any would-be fire sites. Therefore, one can highlight the advantages offered by PVC in case of an unexpected blaze.

Table 4 outlines the main events recorded in the tests with PVC1–3. It is important to emphasize the behavior of all samples in terms of the explosive action, inasmuch as all samples showed concrete spalling on the face exposed to high temperatures as well as the formation of bubbles on the PVC surface not exposed to fire. Figs. 5 and 6 show the appearance of bubbles on PVC1–3 and the concrete spalling for all three samples.

It is important to highlight that, as in all cases, spalling was caused by the mechanical forces generated within the structural element (walls in this case), due to thermal stress and the rapid expansion of moisture within the concrete.

3.1. *Load bearing capacity*

In cases PVC1 and PVC2, a load of 1.6 tf/m was applied to the system with the aid of hydraulic cylinders and beams to guarantee an even distribution of it in the surface of both samples. This load was applied in order to simulate the weight and live load that these panels could support, in other words,

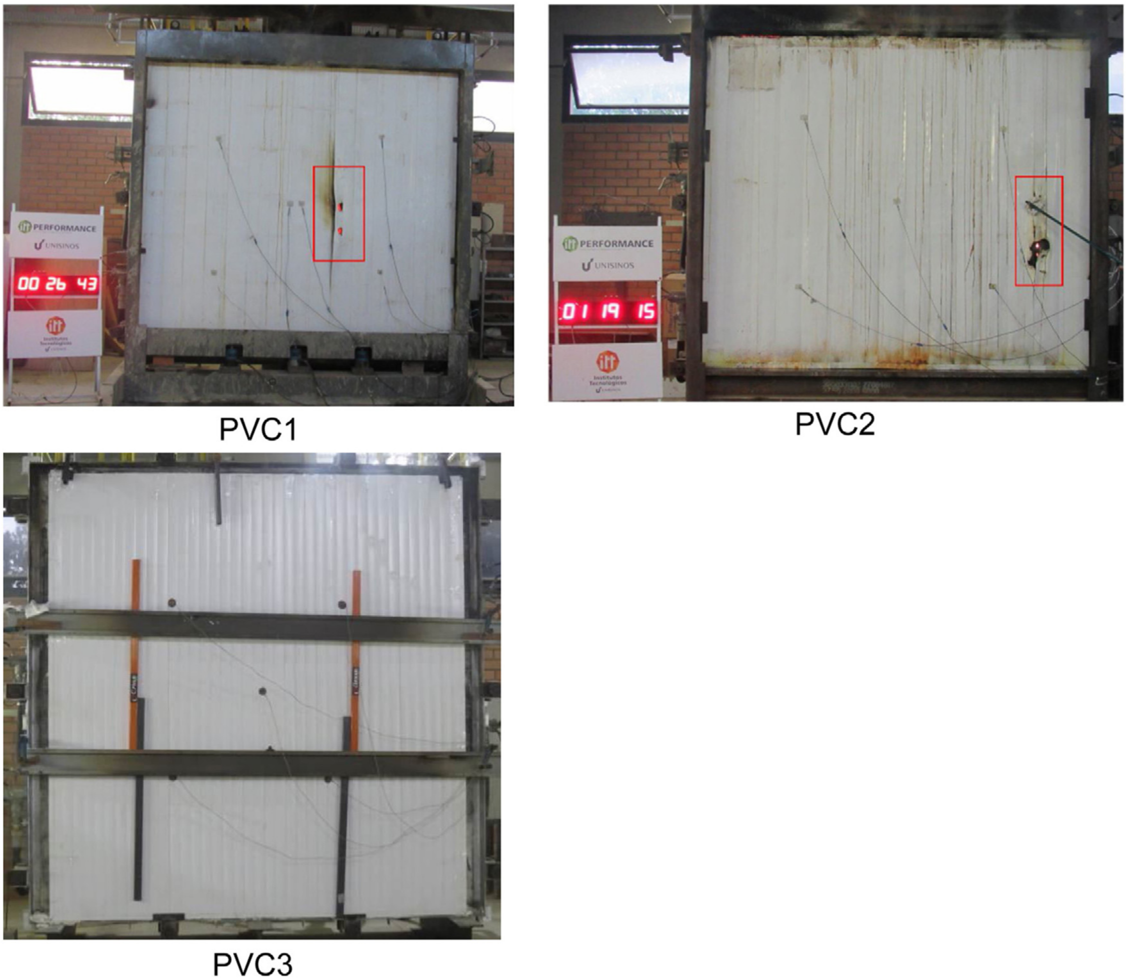


Fig. 7 – Aspects of loss of integrity for samples PVC.1–3.

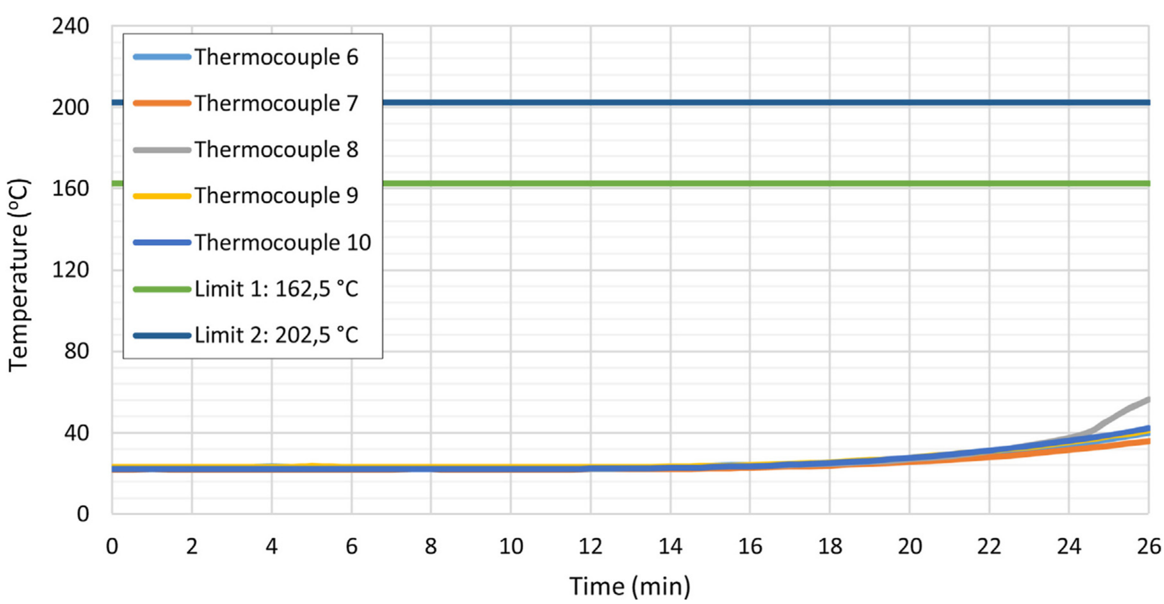


Fig. 8 – Temperature measurements recorded by the thermocouples on the external face of the PVC1 sample.

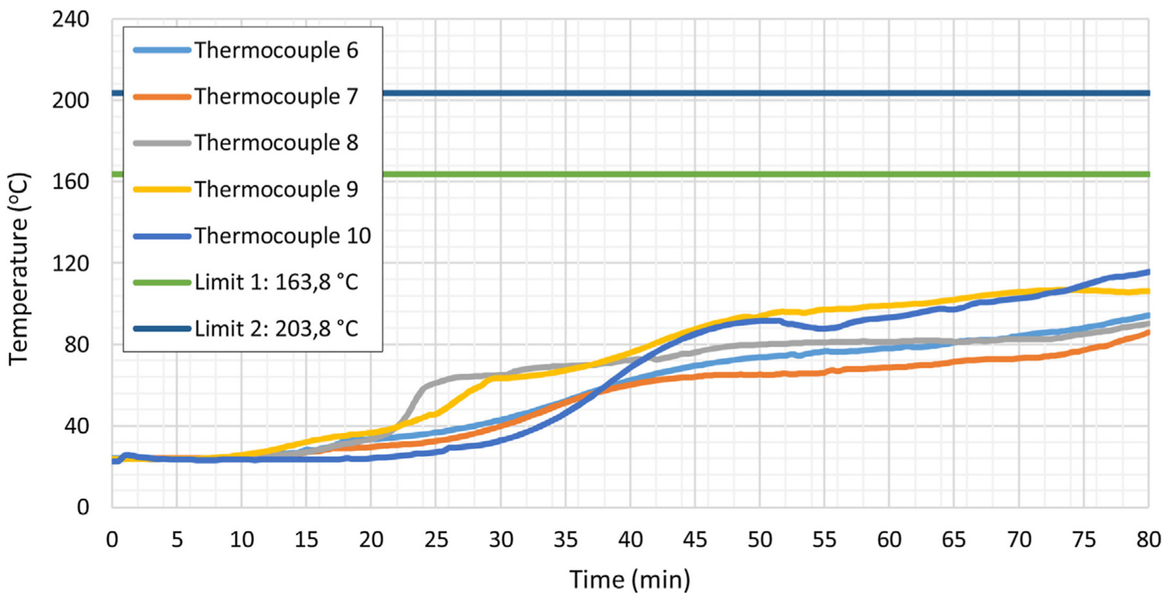


Fig. 9 – Temperature measurements recorded by the thermocouples on the external face of the PVC2 sample.

it was the design load, hence, once the test was finished, this load was removed. After a 20-minute exposure to fire, sample PVC1 underwent a maximum lateral displacement of 1.26 in.(32 mm), thus signaling an unstable behavior.

Hence, the reapplication of the load, expected to be performed 24 h after the end of the test in order to verify its structural stability, was not carried out due to the loss of stability of the sample during the test. Thus, the system evidenced a fire resistance time of 20 min according to ISO 834, considering that only 80% of the test time is to be accounted in the event of loss of stability.

The PVC2 sample manifested a maximum lateral displacement of 2.16 in.(55 mm), which was registered after a 70-minute exposure to fire. Like in sample PVC1, the reapplication of the load was needless due to the loss of stability of the sample during the test. Thus, the system proved a fire resistance time of 64 min according to the norm.

The PVC3 sample (without load application), yielded a maximum lateral displacement of 1.25 in.(31.8 mm) registered after an exposure to fire for 60 min. The system attested a stable resistance to fire, maintaining its original structure except for the presence of some buckling deformations in the panel throughout the entire test. Table 5 displays the load and displacement characteristics of PVC1–3 during the tests applied to them:

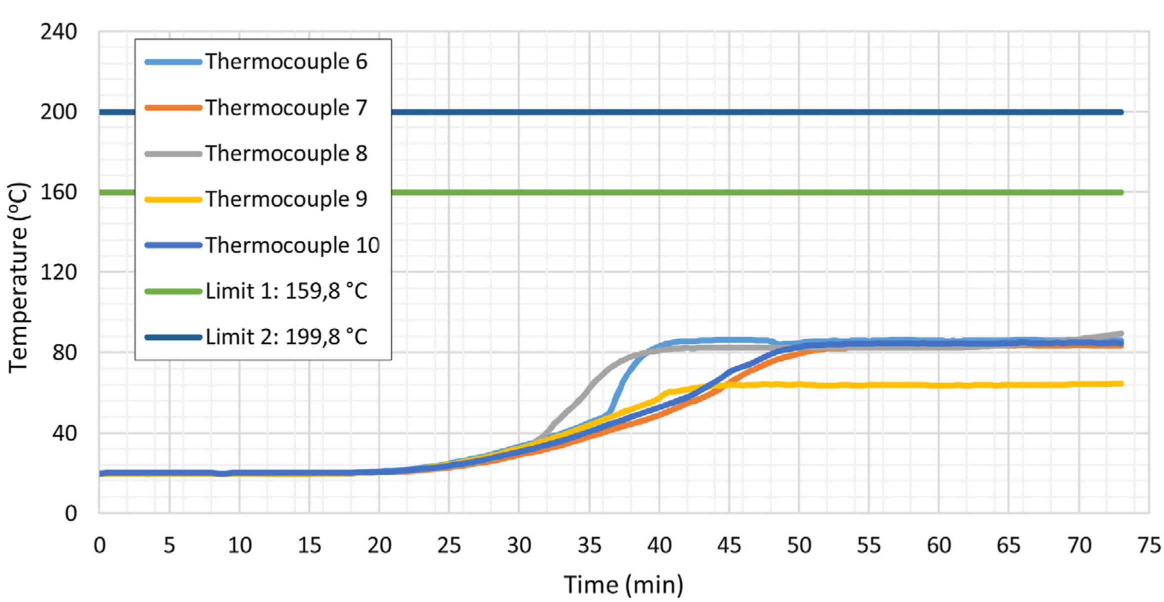


Fig. 10 – Temperature measurements recorded by the thermocouples on the external face of the PVC3 sample.

Table 5 – Summary of load and displacement shown by samples PVC 1–3 during test time.

Time (min)	Load (tf/m)		Displacement (mm)		
	PVC1	PVC2	PVC1	PVC2	PVC3
0	1.5	x	0	0	0
5	1.7	x	7	11	6
10	1.6	x	21	21	12
15	2.3	x	28	27	21
20	–	–	32	30	24
25	–	–	–	36	23
30	–	–	–	41	20
40	–	–	–	43	31
50	–	–	–	45	31
60	–	–	–	50	32
70	–	–	–	55	–
80	–	–	–	54	–

3.2. *Integrity*

For PVC1, no integrity test was carried out because the concrete deployment allowed straight leakage of flames, which originated the loss of system integrity.

Unlike PVC1, the PVC2 sample underwent six integrity tests. None of these tests evidenced any trait of the cotton wool pad inflammation.

The PVC3 sample displayed adequate integrity characteristics during the first 30 min of the test. From this moment on, smoke came out of the external surface of the sample due to the development of fissures, through which some gas leaked out.

As for PVC3, it was observed that it did not affect the results for the cotton wool pad test, which indicated the outflow of gases. Fig. 7 illustrates all events related to the loss of integrity of the three samples (PVC 1–3) tested in the experiment.

3.3. *Thermal insulation*

For the PVC1 sample, the average environment temperature at the beginning of the fire test was 22.5 °C (72.5 °F), the average temperature limit of the thermocouples read 162.5 °C (324.5 °F) and the temperature limit for each thermocouple reached 202.5 °C (396.5 °F). None of the temperature limits were either attained or exceeded during the course of the test.

With reference to PVC2 sample, the average environment temperature at the beginning of the fire test was 23.8 °C (74.84 °F), the average temperature limit of the thermocouples read 163.8 °C (326.84 °F) and the temperature limit for each thermocouple reached 203.8 °C (398.84 °F).

In regard with the PVC3 sample, the system presented thermal insulation conditions during the entire course of the test. The environment temperature at the beginning of the fire test was 20.8 °C (69.44 °F). The sample effectively acted as a thermal insulator, reason which explains why the temperature and the average temperature of the thermocouples did not reach the measuring criteria against fire according to ISO 83435 (180 °C and 140 °C, respectively) on the face not exposed to fire.

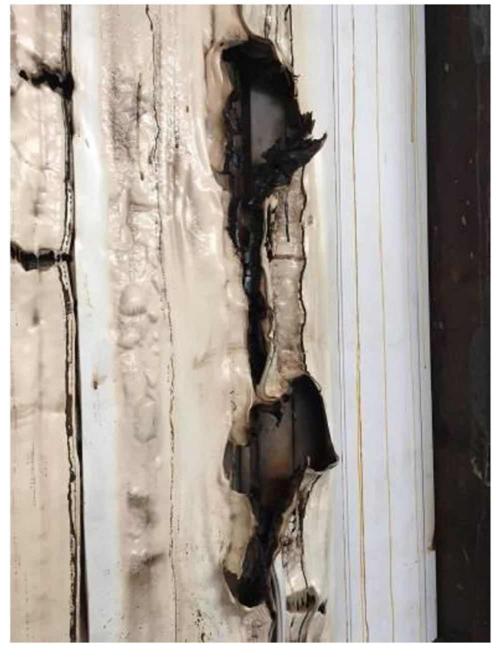


Fig. 11 – Typical aspect of melting and deformities of the PVC profiles tested.

The point temperatures measured by the thermocouples on the face not exposed to fire are presented in Figs. 8, 9 and 10.

3.4. *Final aspects*

Just after the completion of the test was finished, each sample was left untouched until it cooled down by itself, decoupling it from the vertical furnace to inspect its final features in the area located inside the oven. In both PVC1 and PVC2, melting signs as well as concrete spalling were detected on the faces of the PVC profiles, directly exposed to high temperature fire. A different effect was observed on the faces not exposed to high temperatures: An unquantified number of bubbles formed there and unmeasured deformities in the PVC profiles occurred as shown in Fig. 11.

In PVC3, some changes were spotted on the internal face of the PVC panel and in its joints. Figs. 12 and 13 displays the how each tested sample ended up.

3.5. *Discussion*

Due to the limited literature and experimental data on this type of concrete confinement, the current research analyzed and evaluated the fire resistance behavior of 3 types of PVC SIP formwork concrete panels (structural and non-structural) and compared their results among themselves. The importance of considering these two types of systems, structural and non-structural, lies in including the simulation of both representative scenarios of the daily use of residential structures in case of a fire (Fig. 13).

Nowadays, various systems of insulation and fire protection have been developed worldwide for different types of structures, in different situations and construction materials. But, taking into account that the researches about this topic

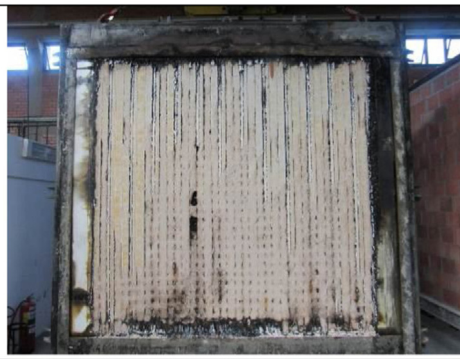
Sample	Final aspects of the sample	
	Internal	External
PVC1		
PVC2		
PVC3		

Fig. 12 – Final aspects of the samples tested.

so far focus on studying other structural elements (columns, beams, etc.) or analyzing other parameters, in this paper, an experimental investigation was carried out on the fire resistance behavior of concrete panels (with and without structural function).

Considering that all the systems preserved PVC profiles with very similar properties, it is evident that the compressive strength factor of concrete significantly influenced the integrity parameter of the samples. It was evidenced that as the value of compressive strength factor increased, the integrity of the structure was improved, avoiding the passage of flames to the external environment. Consequently, the time of appearance of crackles and the total time of fire resistance of the samples were enhanced. It should be highlighted that these results can be influenced by determinant factors in the mix designs of the concretes that are used as the water/cement ratio (w/c), particle size range of coarse aggregate, content and types of binders and mineral admixtures content.

In addition, the loading condition was also a determinant factor for the fire resistance performances of the panels. The system that was not loaded developed a better behavior than the two loaded, in their total test times and their structural stability, as it was expected. The first one remained stable throughout the test (despite some panel buckling) unlike the other two.

Another very interesting event to be highlighted is that the formation of bubbles on the surface not exposed to fire of the PVC profiles of the samples occurred in the period of 15-min to18 min, in which the temperature range is 20 °C–30 °C (68 °F–86 °F). It was also noticed that PVC coating had no effects on the lateral displacements of the panels suffered

Fig. 13 – Details of the final aspect of the concretes surfaces.

during the tests, and that for the sample without loading, after 60 min of exposure to fire, the external surface manifested an average temperature of approximately 80 °C (176 °F), whereas the conventional reinforced concrete panel normally reports an average temperature of approximately 90 °C (194 °F) [6].

On the other hand, if PVC is compared to wood, as materials that can be used for formwork for the construction of walls, we find that the temperature necessary to inflame PVC is 150° higher than that of wood. Parallel, once the flame has been extinguished, the PVC is self-extinguishing and, in addition, does not ignite spontaneously. The release of heat from PVC is quite inferior to that of other materials including wood, and we know that the extent to which the heat is released is determinant for the intensity of a fire and its speed of propagation. Therefore, the use of PVC (with coefficient of thermal conductivity slightly lower than that of wood: 0.17 W/m^2 °C, compared to 0.23 W/m^2 °C), can contribute to the reduction of fire risks, and at the same time reduces the speed of propagation of the fire in case of occurrence.

Additionally, taking into account that its molecule is made up of 57% chlorine (obtained from common salt) and only contains 43% ethylene (derived from petroleum), PVC could be defined as an eco-friendly material since conserves natural resources by using only a part of hydrocarbons. This, without mentioning that the energy consumption in its manufacturing process, with respect to materials such as steel and aluminum, are notably lower, and that it is a totally recyclable material. It can be incinerated, used in landfills or simply re-used for the production of plastics.

Despite the myths that exist worldwide about the toxicity of the smoke PVC, investigations such as the reports of the fires of the factory at Lengerich and at the airport in Dusseldorf demonstrate that the quantity of dioxins formed from the combustion of PVC is not significant to cause people poisoning [34]. While it is true that carbon monoxide (CO) and hydrogen chloride (HCL) are the two main gases produced in the PVC combustion process, the concentration of HCl is not constant during a fire, but decreases in the course of the combustion, especially in the presence of typical building materials such as plaster and cement (as it is in this case) and in the presence of moisture [34].

Finally, taking into account then that, apparently, PVC smoke does not represents an increased health risk above the unavoidable and highlighting a very important characteristic of this material, as it is the low rate of evolution of heat that it has, the authors consider that this is a good system option for the construction of walls allowing protection of the houses against moisture, reducing the risk of fire and offering greater comfort by reducing the effects of heat or cold, being able to be destined to residential structures of daily use without any concern. This is also supported by the small amount of PVC present in this type of panels, being this only the formwork formed by a thin coating of this material.

4. Conclusions

The fire resistance behavior of three different concrete panels constructed with PVC SIP formwork of dimensions 124.01 in × 110.24 in × 3.15 in was evaluated according to ISO 834 and compared to each other. Among these three systems tested, two had load-bearing capacity and one did not, of which the following conclusions may be drawn:

1 The PVC1 panel test lasted 26 min, reaching a maximum lateral displacement of 32 mm and developing an explosive crevice in the concrete what led to the loss of integrity of the system, so that no integrity test could be performed.
2 The PVC2 panel achieved a total fire resistance time of 64 min, reaching a maximum lateral displacement of 55 mm, losing stability during the test. Despite this, six integrity tests were carried out confirming positive results.
3 The PVC3 panel achieved a total fire resistance time of 60 min and reaching a maximum lateral displacement of 31.8 mm. The sample maintained his integrity characteristics for the first 30 min of the test, but later smoke appeared on the external surface of the wall due to the development of fissures, sufficient to allow the passage of gases.

Based on the results of this experimental investigation, it can be inferred that the thermal insulation performance of the PVC coated concrete panels was slightly better than that of the reinforced concrete panels with a traditional removable formwork, according to what is reported in the literature [6]. In addition, it can be said that concrete strength significantly affects the structural stability of the panels (under load), even in this type of panels when subjected to high temperatures. It can be attributed the low times of fire resistance, the absence of reinforcement and the use of loading, when compared with the results obtained by bibliographical research [6]. Regarding the other parameters of analysis, no significant alterations were observed in comparison with the conventional formwork system.

On the other hand, it is presumed that the attributes of the SIP PVC formwork can contribute significantly to the conservation of ecosystems. The alternative of installing PVC for the formwork of panels, instead of wood for example, is due to the importance of creating awareness of the need to conserve forest resources and promote their rational use, being this is a material friendly to the environment.

This combination of qualities results in the inclusion of PVC within the group of organic materials of better technical classification, being a resistant material, antibacterial, moldable, hygienic and recyclable, ideal for fire prevention, but mainly to turn houses into Healthy and Sustainable Housing.

Knowing these positive findings, it is recommended to analyze more thoroughly these types of PVC SIP formwork concrete panels for a better understanding of their behavior when subjected to fire conditions, especially considering the possible toxic gases release, the chemical and mineralogical aspects and occupational risk factors, some of its main concerns still today. Furthermore, for future researches, it is suggested that these results be considered as an input of experimental data for comparison with theoretical data obtained from numerical investigations.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors wish to express their gratitude to the Technological Institute in Civil Construction Performance of the Unisinos University (itt Performance), for supporting this research work.

REFERENCES

[1] International Association for the study of Insurance Economics. World fire statistics. In: Information bulletin of the world fire statistic centre; 2010. p. 3.
[2] Ji Gefu, Li Guoqiang, Li Xiugang, Pang Su-Seng, Jones Randy. Experimental study of FRP tube encased concrete cylinders exposed to fire. Compos Struct 2008;85:149–54.
[3] Global Concepts in Residential Fire Safety: Part 3 - Canada, Puerto Rico, Mexico, and Dominican Republic (2009) Centers for Disease Control and Prevention, prepared by TriData Corporation.
[4] Fire death rate trends: an international perspective. Topical fire report series, vol. 12; 2011. Issue 8.
[5] International association of fire and rescue services. World fire statistics, vol. 20. Center of Fire Statistics, CTIF; 2015. p. 63.
[6] Gil A, Pacheco F, Christ R, Bolina F, Khayat K, Tutikian B. Comparative study of concrete panels' fire resistance. ACI Mater J 2017;114(5):755–62, http://dx.doi.org/10.14359/51689715.
[7] Jansson R. Fire spalling of concrete: theoretical and experimental studies, doctoral thesis. Stockholm, Sweden: Vetenskap Och Konst; 2013. p. 3.
[8] Wattick J, Chen A. Development of a prototype fiber reinforced polymer— concrete filled wall panel. Eng Struct 2017;147:297–308.
[9] Recycling Concrete. Cement sustainability initiative (CSI); 2009. p. 3.
[10] Yan Z, Pantelides C, Reaveley L. Posttensioned FRP composite shells for concrete confinement. Compos Struct 2007;11:81–90, http://dx.doi.org/10.1061/(ASCE)1090-0268(2007)11:1(81).
[11] Rousakis T, Tourtouras I. RC columns of square section–passive and active confinement with composite ropes. Compos Part B Eng 2014;58:573–81, http://dx.doi.org/10.1016/j.compositesb.2013.11.011.
[12] Rousakis T, Kouravelou K, Karachalios T. Effects of carbon nanotube enrichment of epoxy resins on hybrid FRP–FR confinement of concrete. Compos Part B Eng 2014;57:210–8, http://dx.doi.org/10.1016/j.compositesb.2013.09.044.
[13] Fakharifar M, Chen G, Arezoumandi M, ElGawady M. Hybrid jacketing for rapid repair of seismically damaged reinforced concrete columns. Transport Res Rec 2015;2522:70–8, http://dx.doi.org/10.3141/2522-07.
[14] Eramma H, Madhukar NJ. Experimental investigation on PVC encased columns. Int J Res Eng Technol 2015;04(09):39–44.
[15] Awham M, Salih ZGM. A study of some mechanical behavior on a thermoplastic material. J Al-Nahrain Univ 2011;14(3):58–65.
[16] Al-Malaika S, Golovoy A, Wilkie CA. Chemistry and technology of polymer additives. Blackwell Science; 1999.
[17] Titow WV. PVC technology. Springer; 1994.
[18] Gupta P. Confinement of concrete columns with unplasticized poly-vinyl chloride tubes. Int J Adv Struct Eng 2013;5:1–19, http://dx.doi.org/10.1186/2008-6695-5-19.
[19] Wang J, Yang Q. Experimental study on mechanical properties of concrete confined with plastic pipe. ACI Mater J 2010;107(2):132–7.
[20] Wahab N, Soudki K. Flexural behavior of PVC stay-in-place formed RC walls. Constr Build Mater 2013;48:830–9, http://dx.doi.org/10.1016/j.conbuildmat.2013.07.073.
[21] Abduljabar Abdulla N. Concrete filled PVC tube: a review. Constr Build Mater 2017;156:321–9, http://dx.doi.org/10.1016/j.conbuildmat.2017.08.156.
[22] Scott B, Wahab N, Al-Mayah A, Soudki K. Effect of stay-in-place PVC formwork panel geometry on flexural behavior of reinforced concrete walls. Structures 2016;5:123–30.
[23] Havez A, Wahab N, Al-Mayah A, Soudki K. Behaviour of PVC encased reinforced concrete walls under eccentric axial loading. Structures 2016;5:67–75, http://dx.doi.org/10.1016/j.istruc.2015.09.003.
[24] Canadian Standards Association, CSA A23.3 Design of concrete structures; 1994.
[25] American Concrete Institute (318R-04) Building code requirements for structural concrete (318-04) and commentary; 2004.
[26] Chahrour A, Soudki K, Straube J. RBS Polymer encased concrete wall. Part I: experimental study and theoretical provisions for flexure and shear. Constr Build Mater

2005;19(5):550–63, http://dx.doi.org/10.1016/j.conbuildmat.2004.12.003.
[27] EN 1991-1-2. Eurocode 1: actions on structures - Part 1-2: general actions - Actions on structures exposed to fire; 2002.
[28] EN 1996-1-2. Eurocode 6: design of masonry structures - Part 1-2: general rules - Structural fire design; 2005.
[29] EN 1363-1:1. Fire resistance tests - part 1: general requirements; 1999.
[30] International Organization for Standardization. Fire-resistance tests—elements of building construction—part 1: general requirements (ISO 834-1); 1991. p. 53.
[31] Bolina F, Prager G, Rodrigues E, Tutikian B. Avaliação da resistência ao fogo de paredes maciças de concreto armado. Ambiente Construã-do 2015;15(4):291–305, http://dx.doi.org/10.1590/s1678-86212015000400051.
[32] Bolina F. Avaliação experimental da influência dos requisitos de durabilidade na segurança contra incêndio de protótipos de pilares pré-fabricados de concreto armado. Brazil 2016.
[33] Associação Brasileira de Normas Técnicas (ABNT). Paredes Divisórias sem Função Estrutural—determinação da resistência ao fogo: método de ensaio (NBR 10636); 1989. p. 7.
[34] Obloj-Muzaj M. Fire performance of PVC. Int Polym Sci Technol 2001;28(3):98.